Chapter 4

RADIANT COOLING IN US OFFICE BUILDINGS: DESIGN OF THE MODELING PROJECT

4.1 Introduction

Chapter 2 discussed the energy and peak power savings potential of buildings equipped with radiant cooling systems. Such buildings are currently built in Europe, either as new construction or as retrofits. Despite general efforts to promote energy efficient technologies on the US market, traditional all-air systems are still installed in new and retrofitted commercial buildings in the US. There is no evidence that the US air-conditioning market will adopt and promote radiant cooling systems in the near future.

Attempting to explain the absence of radiant cooling systems from the US market is beyond the scope of this thesis. A complete explanation would very likely require the description of a complex interaction of technical, economic, social, and cultural factors. Instead of undertaking this ambitious task, this thesis limits itself to investigating one technical aspect of the operation and functioning of buildings equipped with radiant cooling systems: the compatibility of radiant cooling systems with the range of climates characteristic for the United States. There is no doubt that radiant cooling systems can *cool* buildings located in any climate, if the peak specific cooling load is below 140 W/m^2. The notion of "compatibility" is used here to indicate that it is currently unclear whether (1) a radiant cooling system can be operated to provide *comfortable conditions* inside a building located in any climate, and (2) the control strategies used to ensure comfort in "problem-climates" still allow the radiant cooling system to save energy and peak power when compared with a traditional all-air system.

4.2 The Issue

Although recent information regarding Western European building practices indicates that implementation of radiant cooling systems is currently in progress in commercial buildings [1], the available information regarding the performance of buildings equipped with radiant cooling systems is limited to data gathered from a few buildings in Germany and Switzerland. According to these data, buildings recently equipped with radiant cooling systems consume less energy and require less peak power for conditioning, than similar buildings equipped with traditional all-air systems. Furthermore, there are virtually no occupant complaints regarding indoor comfort in these buildings. However, because the available data are scarce, it is possible that all the buildings that have been studied are located in climates in which radiant cooling systems are inherently more efficient than all-air systems (for instance, warm, dry climates). Therefore, it is difficult to argue that the choice of a radiant cooling system instead of an all-air system would make *any* commercial building more energy efficient and more comfortable.

This thesis addresses the topic of compatibility between radiant cooling systems and the climates in which the buildings are located mainly through the issue of moisture control in the operation of radiant cooling systems. Chapter 2 has stated that, if the dew-point of the indoor air drops below the surface temperature of the radiant cooling system, condensation will appear on the radiant surface. Condensation is unacceptable from the point of view of occupant comfort, as well as because it can cause damage to the building structure, building finishes, and the radiant system itself. Chapter 2 has also stated that indoor moisture levels can be controlled, and the risk of condensation can be reduced, by dehumidifying the supply air. However, in humid climates, this dehumidification process could be so energy intensive that it may exceed the savings achieved by the choice of the radiant system instead of an all-air system.

There is no known research that has addressed the climate-compatibility of radiant cooling systems in detail. Common sense suggests that the climates where buildings equipped with radiant cooling systems would function with a small risk of condensation, and achieve substantial energy and peak power savings, are the warm and hot dry climates. If the reverse of this statement were true, namely that buildings equipped with radiant cooling systems could not function optimally and/or would achieve minimal savings in other climates, radiant cooling systems may prove inadequate or unattractive for most of the US territory. Such a conclusion could provide a partial explanation for the absence of radiant cooling systems from the US market.

4.3 The Parametric Study

The lack of information regarding the performance of radiant cooling systems in different climates is partly due to the absence of a building simulation program that can model heat transfer phenomena in buildings equipped with radiant cooling systems. The program RADCOOL, described in Chapter 3 and Appendix A, was specifically designed to fill this gap. RADCOOL can calculate loads, heat extraction rates, air temperature and surface temperature distributions in a building equipped with a radiant cooling system. As it can evaluate system sizing and system configuration, RADCOOL results can also assist in establishing design parameters for radiant cooling systems (for example, mass flow for the cooling water, pipe spacing, etc.).

Access to RADCOOL offers the possibility of conducting parametric studies. In particular, a parametric study can be designed to investigate the topic of climate-compatibility of buildings equipped with radiant cooling systems. This thesis conducted a parametric study consisting of modeling a single-zone space, in an office building with pre-established construction, orientation, occupancy rates, etc., under different weather-imposed boundary conditions.

The parametric study was designed to provide two types of results. First, the study would show whether buildings equipped with radiant cooling systems might have condensation problems in any of the climates characteristic for the US. Second, the study would allow the calculation of the energy consumption and peak power demand of the radiant cooling system. By comparing these results with similar results obtained for the same building equipped with a traditional all-air system, some estimates can be made regarding (1) the energy and peak power savings potential of the radiant cooling system, and (2) the dependence of these savings on the climate in which the building is located.

To achieve the objectives described above, the modeling project conducted by this thesis consisted of parallel RADCOOL [2] and DOE-2 [3] simulations modeling the indoor conditions of the selected office space. The RADCOOL program modeled the space as conditioned by a radiant cooling system. To study the influence of night ventilation on the indoor environment of the space, the study investigated two different night ventilation strategies.

The DOE-2 program was used to model the same office space as conditioned by a variable air volume (VAV) system during occupancy hours, and by a constant volume system (CV) during the time when no building occupants are present. The design parameters of the all-air system are finely-tuned so that the indoor air temperature and humidity ratio during occupancy hours, and the outside air ventilation flow during the whole day, are virtually the same as those obtained inside the space equipped with the radiant cooling system.

To investigate the influence of geographical location on the performance of the two systems, RADCOOL and DOE-2 simulations were carried out, and the indoor conditions obtained, for the test space subjected to different climate-imposed boundary conditions. For each climate, the results were examined to determine the presence or absence of condensation, as well as whether the indoor air temperature and relative humidity met standard comfort requirements. Then, in each climate, estimates were made for the energy consumption and the peak power demand of the radiant cooling system and the all-air system.

The author notes that an ideal evaluation of the savings potential of radiant cooling systems in commercial buildings would involve a comparison between radiant cooling system performance and the performance of a traditional all-air system that provides the same *indoor comfort* to a given space. Such a comparison could be achieved by designing the two systems to match a comfort index for the overall sensation of indoor thermal comfort. For example, the “predicted mean vote” (PMV) index predicts the mean response of a large group of people according to a thermal sensation scale [4]. Two spaces characterized by the same PMV are considered to offer the same level of thermal comfort. When estimating radiant cooling performance, a PMV-based comparison would be beneficial because the presence of a relatively large cooling surface in the space reduces the mean radiant temperature inside the space. Consequently, the radiant cooling system can provide a given level of comfort at an indoor air temperature higher than that necessary to the all-air system to provide the same level of comfort. However, the calculation of the PMV requires access to information regarding all four physical comfort parameters (air temperature, partial pressure of water vapor, mean radiant temperature and air velocity). As stated in Chapter 3, DOE-2 does not provide information regarding indoor surface temperatures. In addition, in their present stage of development, neither DOE-2 nor RADCOOL provide the information necessary in an estimate of the average indoor air velocity. Consequently, the parametric study conducted in this thesis is based on matching only two indoor comfort parameters: the indoor air temperature and humidity. Due to the lack of information regarding the other two physical comfort parameters, the author cannot estimate how the performance results reported in this thesis might related to performance results obtained by conducting a parametric study matching the indoor comfort in the space under study.

4.4 Working with the RADCOOL-Imposed Constraints

Chapter 3 states that RADCOOL is currently able to simulate (1) a single-zone space, and (2) a week-long modeling period. Due to these constraints, the parametric study described in the preceding section could not be carried out in an ideally general and detailed way. This section reviews the assumptions made in order to conduct the study, and discusses the uncertainties introduced by making these assumptions.

Regardless of its assumptions and uncertainties, the parametric study has certain merits. First, it establishes a methodology for conducting climate-compatibility investigations. Second, it is reproducible, therefore it can be extended as soon as the calculation capacities of computers evolve. Third, to the author's knowledge, it represents the first effort to study the performance of buildings equipped with radiant cooling systems under different climate conditions. Finally, its results suggest climate-dependent trends in the energy consumption and the peak power demand of a radiant cooling system.

4.4.1 The base-case building

This study assumes a commercial building context because the available information regarding the performance of radiant cooling systems in Western European buildings suggests that the commercial sector represents the main market for these systems [1]. This can be explained based on the need for strict moisture control in buildings equipped with radiant cooling systems, and on the fact that in commercial buildings the indoor moisture sources are limited (occupants, coffee makers, plants), and they can be controlled relatively easily. Among the existing types of commercial buildings, the study focused on office buildings because human activity in office buildings is quasi-predictable.

The study is conducted on an imaginary building designed by the International Energy Agency to serve as base-case for building energy and indoor air quality studies [5]. The design corresponds to a medium-size office building with single- and multi-occupancy offices located on the building facades, and with a core space dedicated to utility activities (see Figure 4.1). The building is rectangular and its longer facade is oriented 45° east of north. Figure 4.1 shows only one floor of the building. In what follows, the author will refer to this floor as “the whole building”.

To ensure compatibility between this base-case building and US building standards, the study focuses on a building structure complying with the California Title 24 building standard [6]. It features a curtain-wall construction (see Figure 4.2) with a U-value of 0.45 W/m^2-K for the opaque part. The vision glazing of the curtain-wall construction consists of double-pane windows with a center-of-glass U-value of 1.31 W/m^2-K. No drapes or mechanical shading are simulated for the windows. The interior walls of the building consist of a 6-cm air layer sandwiched between two layers of plasterboard, each 1-cm thick (Figure 4.2). The U-value of the interior walls is 1.95 W/m^2-K.

The ceiling and floor are made out of 32-cm thick reinforced concrete. When the building is equipped with a radiant cooling system, the spaces have an additional dropped panel system made out of 20-cm wide aluminum panels with water pipes attached on the plenum side of the panels. The panel system covers the entire dropped ceiling. The plenum delimited by the panel system and the reinforced concrete ceiling is 10 cm deep.

The material properties simulated in the parametric study are presented in Table 4.1.

TABLE 4.1. Material properties simulated in the parametric study.

	Density [kg/m^3]	**Specific heat [kJ/kg-K]**	**Conductivity [W/m-K]**
Concrete	2400	1100	1.80
Glazing	2460	750	0.80
Insulation	48	840	0.06
Gypsum board	800	1090	0.16
Plaster board	900	800	0.21
Aluminum	2770	875	177.0

It is difficult to evaluate the uncertainty introduced in the results by this particular choice of a base-case building. In an ideal situation, the parametric study would be repeated for a large number of building types, and the results would be compared to those obtained by the present study. However, given the current capabilities of RADCOOL, as well as the time frame of a dissertation, this task is unrealistic. Still, as Chapter 5 will show, the

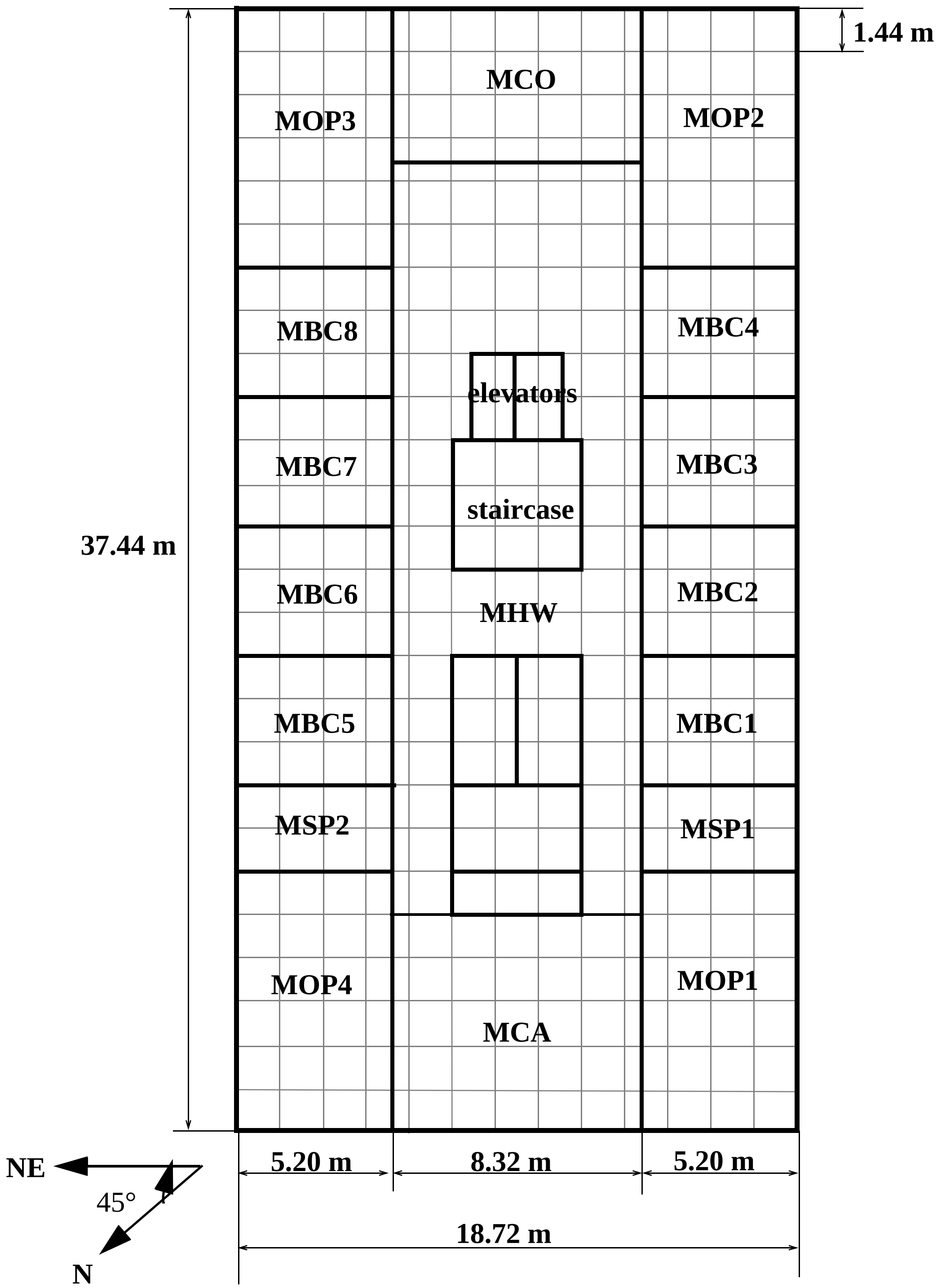

Figure 4.1. Base-case building orientation and layout.

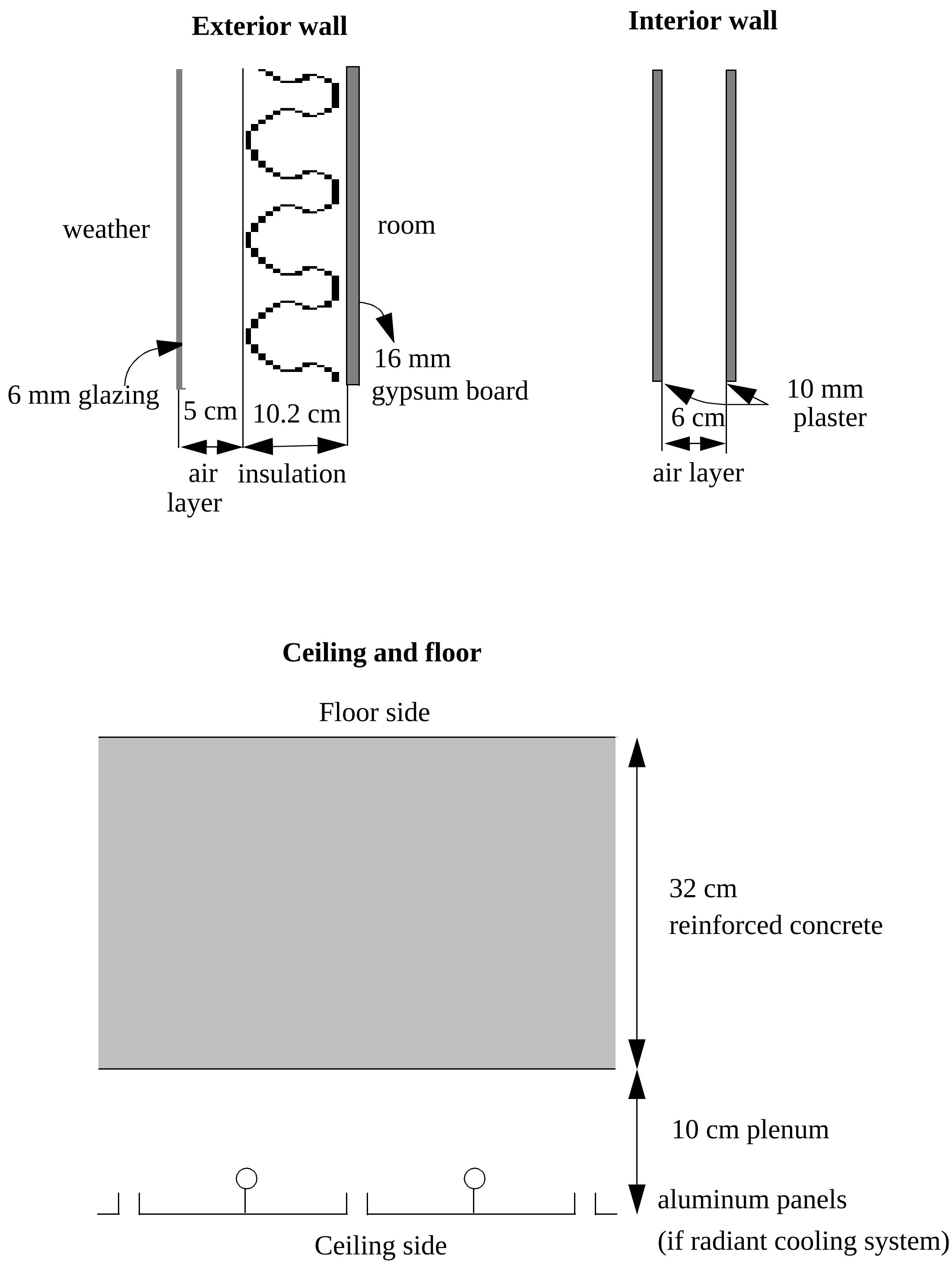

Figure 4.2. Base-case building construction for the parametric study.

parametric study was extended by performing a few additional simulations. The additional simulations show that the conclusions of the study would remain qualitatively the same, even though the results of the study would be quantitatively different for a lighter building structure.

4.4.2 The base-case space

The choice of a space

Because the modeling capabilities of RADCOOL are limited to a single-zone space, conducting the parametric study involved the choice of one room of the base-case building. The character of the RADCOOL requirements, as well as the layout of the base-case building, influenced the choice of the space as follows.

As discussed in Chapter 3, a space can be simulated in RADCOOL only if its internal loads and boundary conditions are known. Because the base-case building selected for this study does not exist in reality, information describing its indoor conditions can only be obtained by modeling the building with a different program (for instance, with DOE-2). However, the boundary conditions obtained from a different program would allow the assumptions embedded in that program to influence the results of the RADCOOL simulation. It would therefore be preferable to obtain the boundary conditions in a different manner.

An examination of the building layout in Figure 4.1 leads to the conclusion that different spaces require different amounts of data for simulation. For example, the boundaries of the corner offices (MOP1-4), the conference room (MCO), the cafeteria (MCA), or the hallway (MHW) are more complex. By contrast, the simulation of some of the middle-of-facade spaces presents less difficulty.

Since the spaces MBC1-4 and MBC5-8, respectively, have the same exposure and internal loads, it is possible that they may have virtually identical indoor conditions. Preliminary DOE-2 simulations verify that the air temperatures of the spaces MBC1-4 and MBC5-8, respectively, differ by no more than 0.1 °C at all times. Consequently, heat transfer through the side walls of spaces MBC2-3 and MBC6-7 can be neglected. A similar argument can be developed regarding the boundary conditions on the ceiling and floor of the spaces MBC2-3 and MBC6-7. If the space to be modeled is located on a middle floor (not a basement, and not a top floor), it is very likely that the indoor conditions in the spaces immediately above and below are the close to those in the given space.

The only boundary condition remaining to be established is that on the “back walls” of spaces MBC2-3 and MBC6-7. Figure 4.1 shows that the “back walls” separate the individual spaces from the central hallway (MHW). Since the hallway is not subject to solar loads, it is possible that the conditions inside the hallway do not vary very much over time. Preliminary DOE-2 simulations verify that, if the hallway is mechanically conditioned, its indoor air temperature remains virtually constant. Once established, this constant temperature can serve as a boundary condition in the RADCOOL simulation.

Because the spaces MBC2 and MBC3 are virtually identical, MBC2 can be considered representative for the thermal behavior of MBC3. Similarly, MBC6 can be considered representative for the thermal behavior of MBC7.

To choose between the spaces MBC2 and MBC6, the author noted that these two spaces differ only through their orientation. The space MBC2 has a south-western exposure, while MBC6 has a north-eastern exposure. The choice of MBC2 would therefore favor the study of a space with large solar loads. In particular, the total load of the space may exceed 100 W/m^2 in some climates. In such a case, the cooling capacity of the radiant cooling system might be exceeded, and the system would fail to adequately condition the space. The choice of MBC6 instead of MBC2 would focus the study on a space with small solar loads, and would therefore eliminate the chance of revealing instances in which the space overheats. To investigate the scenario representing a more difficult situation for the radiant system, the space MBC2 is a better choice for the parametric study than the space MBC6.

Once again, it is difficult to assess the uncertainty introduced by selecting the space MBC2 instead of MBC6, or any other space. To partially address this problem, additional modeling was performed to calculate the energy and peak power savings associated with conditioning the MBC6 space. As in the case of a lighter building structure, the additional modeling shows that the conclusions of the study would remain qualitatively the same, but the results of the study would be quantitatively different, if the study were based on a similar space with a different orientation.

Because the study is limited to the simulation of a single-zone space, it would be interesting to know whether the results obtained by studying the energy consumption and peak power demand due to conditioning the MBC2 space could be used as an estimate for the energy consumption and peak power demand due to conditioning the whole building in Figure 4.1. One possible strategy to estimate the uncertainty associated with extrapolating the results from any particular space to the whole building consists of (1) modeling the whole building, (2) determining the results for a selected space, and (3) calculating the extrapolation factor from the space to the building. In particular, since the purpose of this study revolves around estimating the energy consumption due to air-conditioning the space, the extrapolation factor can be calculated as the building air-conditioning energy consumption divided by the space air-conditioning energy consumption.

It is important to note, however, that for a building with a fixed orientation, structure, internal loads, and design conditions, the extrapolation factor thus calculated depends on the building location (climate at the building site). Repeating the building simulation for a number of locations would generate climate-dependent results for the space air-conditioning energy consumption and building air-conditioning energy consumption. The extrapolation factor corresponding to each climate can then be obtained, and statistical calculations can be used to determine the average climate-induced extrapolation factor, as well as its standard deviation. The relationship between the air-conditioning energy consumption of the space and that of the building could thus be summarized by two statistical terms. These two terms could then be used to predict the building air-conditioning energy consumption from the space air-conditioning energy consumption calculated in any new climate.

There are two major caveats to this method of assessing uncertainty. First, such an extrapolation factor is valuable only if it does not depend on the building location, or if its dependence on building location is weak. Only in this case can the prediction of the air-conditioning energy consumption of the building from the air-conditioning energy consumption of the selected space be relatively accurate. If the extrapolation factor is strongly correlated to the building location, the standard deviation of this factor will be large, therefore it will be difficult to predict the energy consumption of the building from the energy consumption of the space with good accuracy.

The second caveat to this method of assessing uncertainty is that the average extrapolation factor and its standard deviation have so far been considered independent of the building simulation program used to determine them, of the type of air-conditioning system modeled, and of the design conditions specified for the operation of the air-conditioning system. In reality, the two statistical quantities are probably functions of all these factors. However, given the goals of the parametric study, the climate-dependence of the extrapolation factor associated with a given space are most critical.

As an illustration of the above, Figures 4.3 and 4.4 contain the results of a series of DOE-2 simulations for the building in Figure 4.1 equipped with the all-air system. The simulations were performed for 11 US climates.

Figure 4.3 contains the results of the statistical calculations performed on the air-conditioning energy consumption of each individual space in Figure 4.1. The bars in Figure 4.3 represent climate-averaged fractions, calculated as the ratios of the energy consumption of each space to the building energy consumption. The “error bars” represent the climate-induced variabilities of each of these average fractions, calculated as standard deviations.

The results in Figure 4.3 show that the corner spaces MOP1-4, the cafeteria, MCA, and the conference room, MCO, account for relatively large fractions of the building energy consumption. The standard deviations associated with these fractions are large, indicating a strong climate-induced variability. As expected, spaces MBC1-4 and MBC5-8, respectively, account for virtually equal fractions of the building energy consumption. The variability associated with the spaces MBC1-4, is larger than that associated with the spaces MBC5-8. Because all space parameters are the same for MBC1-4 and MBC5-8, this difference in variability can be explained on the basis of the different exposures of these spaces (south-western for MBC1-4, as compared to north-eastern for MBC5-8).

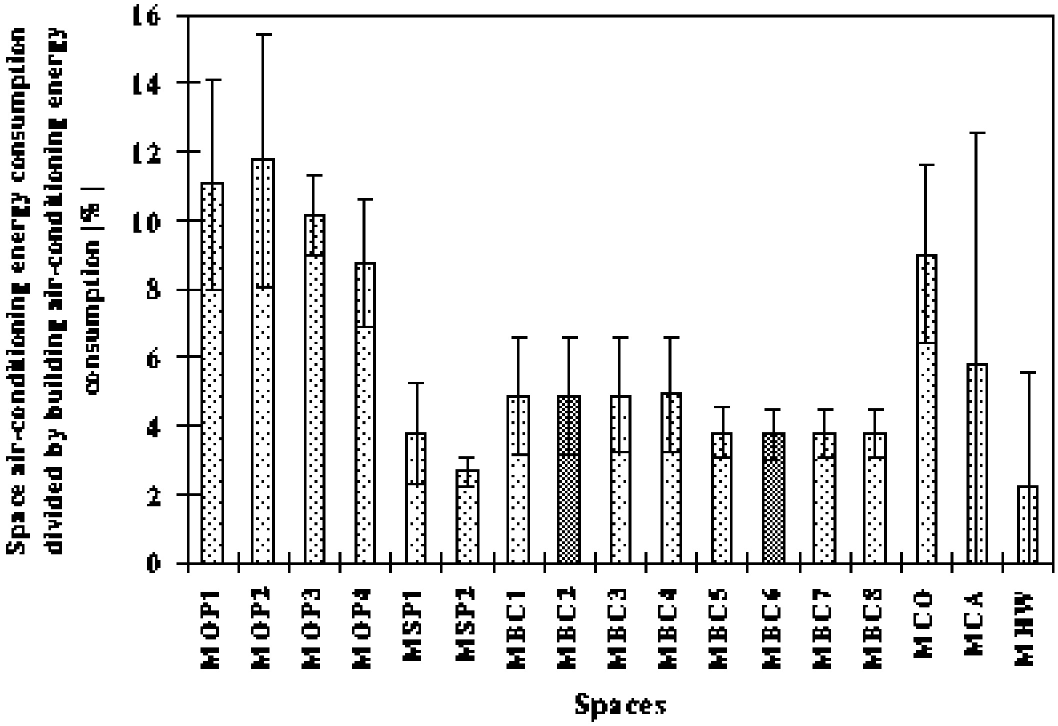

Figure 4.3. Space contributions to the building air-conditioning energy consumption. Statistic performed for 11 building locations.

To use the extrapolation factors in Figure 4.3 in an estimate for the air-conditioning energy consumption of the whole building at a new location, the numerical value of the space air-conditioning energy consumption should be divided by the extrapolation factor of the space (the height of the bar in Figure 4.3 that corresponds to the given space). Because each fraction in Figure 4.3 has an “error bar” associated with it, the extrapolation of the energy consumption of a space to the building energy consumption will result in an energy interval, instead of an energy value. A large energy interval implies that estimating the building air-conditioning energy consumption based on the air-conditioning energy consumption of a given space has a large associated error.

As an example, consider a hypothetical climate in which the building in Figure 4.1 would consume 100 kWh/m^2 annually for air-conditioning. Assume that the air-conditioning energy consumption of each space is also known. The results of predicting the air-conditioning energy consumption of the building from the air-conditioning energy consumption and the extrapolation factor of each space are presented in Figure 4.4.

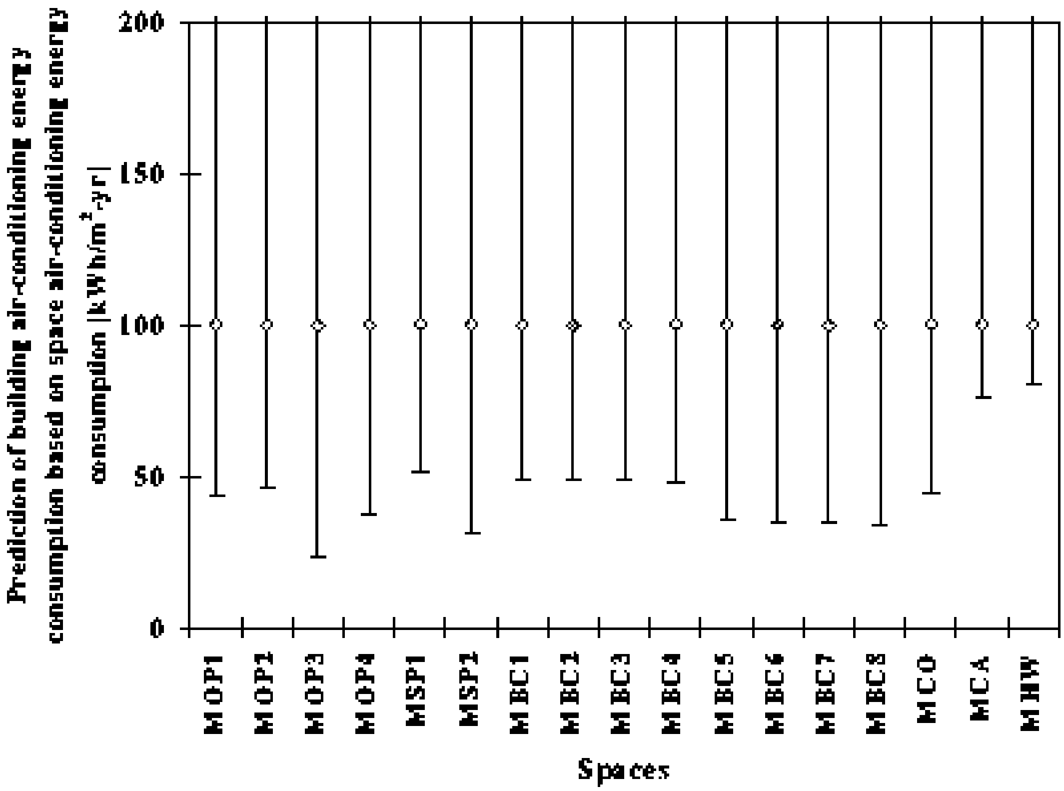

Figure 4.4. Estimate of building energy consumption from space energy consumption. Error bars indicate 90% confidence intervals (n=11).

As the figure shows, using the average value of the extrapolation factor for each space to predict the average air-conditioning energy consumption of the whole building results in the same value of 100 kWh/m^2-yr. However, as each extrapolation factor has its own standard deviation, "90% confidence intervals" can be determined for the prediction corresponding to each space. As the "error bars" in Figure 4.4 indicate, the errors introduced by the extrapolation are very large for all spaces. In conclusion, the extrapolation factor method presented should not be used to estimate the building air-conditioning energy consumption based on the air-conditioning energy consumption of any individual space.

The space characteristics

Space description. The MBC2 office is rectangular with an area of 22.5 m^2 (see Figure 4.1). The facade window area (vision glazing of the curtain-wall construction) is equal to 20% of the floor area of the space.

Internal loads. The model for the MBC2 office space was written to include a variable weekday occupancy pattern in the range of 1 to 2 persons with a weekday schedule from 8 a.m. to 5 p.m.[1] The model describes zero occupancy during the weekend. When "present", each person generates 115 W of heat, of which 75 W are sensible and 40 W are latent. No other sources of latent heat are simulated. The office equipment modeled in the space (computers, printers, lights) has a constant load output of 275 W between 8 a.m. - 5 p.m. on weekdays. No equipment load is simulated during the weekend.

Infiltration. The model for the MBC2 office space describes an infiltration rate of 0.2 ACH (13.5 m^3/h) during the time when the building is not pressurized (the ventilation system is off). An infiltration rate of zero is modeled when the ventilation system is on.

Radiant cooling (RC) system. Cooling water is supplied to the radiant cooling panels at the rate of 180 kg/h and with a constant inlet temperature. The inlet water temperature is selected at each location to adapt the cooling power of the radiant system to the climate-induced cooling load and to maintain the indoor air temperature close to a prescribed design point (24 °C). For the purpose of the study, the RC system is modeled as having a timer-based control. On time coincides with occupancy time (8 a.m. to 5 p.m.).

A constant volume (CV) system provides ventilation. The system supplies outside air only, at the minimum rate specified by ASHRAE Standard 62-1989 [7] (72 m^3/h for a double-occupancy office space). The inlet air temperature is constant and equal to 20 °C. The inlet air humidity ratio is constant and equal to 9.5 g water/kg dry air (65% relative humidity). For the purpose of the study, two ventilation strategies were simulated in order to investigate the influence of overnight moisture buildup due to infiltration on the indoor conditions (see Figure 4.5).

The first ventilation strategy reduces the ventilation air flow during off-occupancy hours (weekend days included). This strategy is mainly beneficial in hot humid climates, as the pressurization of the building by the ventilation system does not allow overnight humidity buildup; this in turn reduces the next day's power demand for the dehumidification of the supply air (to remove the additional latent load).

The second ventilation strategy supplies air at half rate for two hours before occupancy time, and for one hour after occupancy time, and interrupts the ventilation during the remaining 12 hours. During weekend days, the space is ventilated during 12 hours, from 6 a.m. to 6 p.m., albeit at half rate. This strategy is beneficial in any climate, as it ventilates the building before the occupants arrive and after they leave. By switching off the ventilation system for most of the night hours, this strategy reduces the energy consumption and power demand of the air distribution system.

1. As the activity in each office building reflects the type of activity taking place inside, it is difficult to establish a "typical" office building occupancy pattern. The hypothetical 8 a.m. to 5 p.m. schedule used in this study was selected to simplify the interpretation of simulation results.

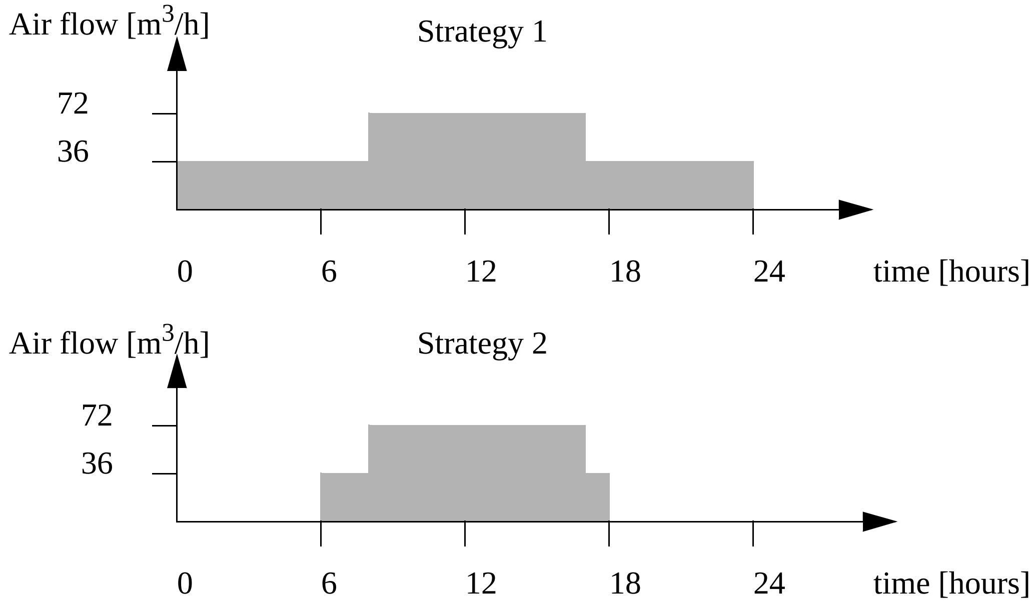

Figure 4.5. Ventilation strategies: schedules for weekday hours.

All-air system. A variable air volume (VAV) system was modeled in DOE-2 during occupancy hours. At each location, the system was designed to match (1) the outside air supply rate of the radiant cooling system, and (2) the indoor air temperature and humidity ratio provided by the radiant cooling system during occupancy hours. To achieve this match, the size of the system, the design cooling coil temperature, the minimum air flow, etc. were established at each location separately.

After occupancy hours, a constant volume (CV) system replaces the VAV system to supply outside air only, at the constant rate of 36 m^3/h. To match the conditions imposed on the radiant cooling system, the CV system functions according the same night ventilation strategies. To provide similar indoor conditions as a basis for comparison, the CV system dehumidifies the outside air to 9.5 g water/kg dry air whenever the outside air humidity ratio is higher than this value.

It is difficult to estimate the uncertainties introduced in the simulation results by the selection of these particular parameters for occupancy schedules, activity levels, equipment power and schedules, the design point, schedules and operation strategies of the two air-conditioning systems, etc., without performing parametric studies for each parameter. The author notes however, that matching the design of the two systems based on the indoor air temperature and humidity introduces a bias in favor of the all-air system. As stated in Section 4.3, using a matching index incorporating the mean radiant temperature would have been to the advantage of the radiant cooling system because the presence of the cooling surface in the space lowers the mean radiant temperature. To match the PMV of the space conditioned by the all-air system, the radiant system would have been able to reduce the cooling power of the radiant surface, which would have translated into lower sensible energy consumption and power demand. However, because DOE-2 and RADCOOL do not provide all the parameters necessary in the calculation of the PMV, it is difficult to estimate the magnitude of the bias introduced in the results by matching the two systems *only* on the basis of the indoor air temperature and humidity.

4.4.3 The locations selected for the parametric study

As RADCOOL simulations take a significant amount of time (about 4 hours of computer time elapse for each simulation on a workstation for 10 days of weather data), the parametric study consists of simulations of the base-case space at only a small number of US locations. To capture the characteristics of a wide range of US climates, the locations were chosen on the basis of a climate classification. The classification criteria reflect the character and purpose of the study.

Climate classification

One of the goals of the parametric study is to compare the energy consumption and peak power demand of a radiant cooling system with those of an all-air system that provides similar indoor air temperature and humidity during occupancy hours. To avoid biasing the results of the study in favor of either system, the climate classification should be based on criteria that have the same influence on the energy consumption of both systems. In general, an air-conditioning system responds to the following weather-induced loads: (1) heat gain by conduction through the building structure; (2) solar heat gain through the windows; (3) infiltration of moist air during periods of non-positive pressure; and (4) conditioning (cooling and/or dehumidification) of the outside air necessary for ventilation.

The heat gain by conduction through the building structure and the solar heat gain through the windows affect the operation of a building conditioning system in similar ways. Consequently, these two components can be examined together when evaluating the response they elicit from the building conditioning system.

The heat gained by conduction and transmission of solar radiation through the building facade is removed from the space by each of the two systems in a characteristic way. The radiant system adjusts water flow and/or water temperature to control the temperature of the radiant surface. The all-air system adjusts the quantity and/or temperature of the recirculation air supplied to the space. Because the two systems use different heat transfer mechanisms to remove the heat from the building, the heat gain through the facade influences the two systems differently. A climate classification based on this factor alone may therefore bias the results of the parametric study in favor of one system or the other.

The moisture buildup due to infiltration during periods of non-positive pressure (for example, when the ventilation is switched off at night) also affects the two systems differently. While both systems use air circulation to remove the accumulated moisture, the air volume supplied to the space by the all-air system once the air supply has been switched on, is much larger than that supplied to the space by the radiant cooling system (the all-air system dehumidifies the *mix* of outside air and recirculation air). Using the moisture buildup parameter as a basis for climate classification would once again bias the results of the parametric study in favor of one system or the other.

Both the radiant cooling system and the all-air system supply the same amount of outside air to the building: the minimum ventilation rate specified by ASHRAE Standard 62-1989 [7] during occupancy hours (72 m^3/h), and half that amount, or zero during off-occupancy hours, depending on the ventilation strategy. As discussed in Chapter 2, for a radiant cooling system the cooling power of the ventilation air is small when compared to the cooling power of the radiant surface. Because the outside air represents a small fraction of the air volume supplied to the space by the all-air system, space cooling is accomplished mainly by the recirculation air. In this study both systems (1) condition the same space located in the same climate, (2) supply the same amount of outside air to the building, (3) dehumidify the supply air to the same level, and (4) provide the same indoor conditions to the building. A climate classification based on the energy associated with conditioning (cooling and/or dehumidification) of the ventilation air ought to introduce the least possible bias in the results.

These considerations led to the following strategy for the climate classification. First, the energy to condition the outside air during an arbitrarily-selected cooling season (May 1 through October 31) was calculated at all US locations for which weather tapes were available.[1] For simplicity, the calculation used the same design conditions for the outside air supply at all locations: the ventilation flow rate corresponding to the first ventilation strategy used in the study (see Figure 4.5), a temperature of 20 °C, and a humidity ratio of 65% (9.5 g water/kg dry air).

Next, the locations were classified in nine groups according to (1) the relative importance of dehumidification in the total energy necessary to condition the ventilation air at each location, and (2) the absolute value of the total energy necessary to condition the ventilation air at each location. This classification allows the groups to contain approximately the same number of locations. Figure 4.6 shows each group as a collection of points located inside contour lines. Finally, at least one location from each group was

1. Weather tapes provide information about the characteristic weather at a given location.

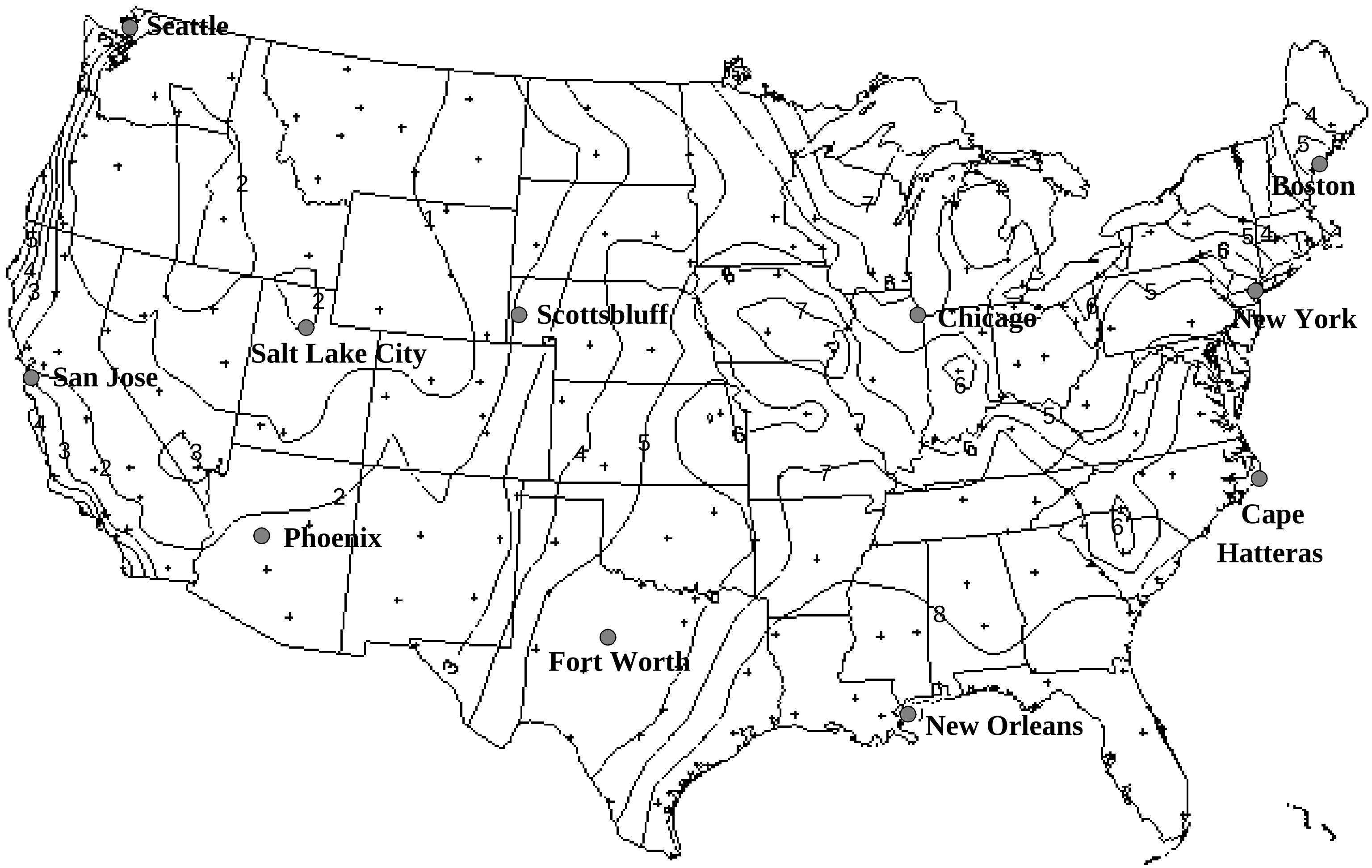

Figure 4.6. Climate classification based on the dehumidification energy and total energy necessary to condition the ventilation air.

selected for the study. Table 4.2 presents the selected locations.

TABLE 4.2. Energy consumption for the cooling and dehumidification of ventilation air. Climate classification and locations selected for the study.

Dehumidification fraction of the total cooling energy for ventilation	Total cooling energy for ventilation [MJ-h/kg]	Group number	Location selected
Dry 0-50%	0 - 5.7	1	Seattle, WA
	5.7 - 12.4	2	Salt Lake City, UT
	12.4 - 54.4	3	Phoenix, AZ Scottsbluff, NE
Moist 50-67%	0 - 18.0	4	Boston, MA San Jose, CA
	18.0 - 28.2	5	Chicago, IL
	28.2 - 88.9	6	Fort Worth, TX
Humid 67-100%	0 - 22.0	7	New York, NY
	22.0 - 59.7	8	Cape Hatteras, NC
	59.7 - 114.7	9	New Orleans, LA

To understand the role of the climate classification in interpreting the results of the study, information was obtained regarding the commercial building stock covered by each of the 9 climate groups. The results are presented in Table 4.3. According to these data, the climate groups 1-3 (dry climates) include only 10% of the commercial building stock in the large metropolitan areas. Climate groups 4-6 (moist climates) and 7-9 (humid climates) each include over 40% of the commercial building stock. Assuming that radiant cooling systems are adequate to handle the different sensible and latent loads occurring in different office buildings, compatibility between the radiant cooling system and the dry climates only (climate groups 1-3), would indicate that the market for radiant cooling in the US is restricted to only a small fraction of the existing commercial building stock. Compatibility between the radiant cooling system and more climate groups would indicate a larger potential market for radiant cooling in the US.

As indicated earlier, condensation problems may arise when a radiant cooling system is installed in a building in which the indoor activity is associated with significant moisture production. Residences, hotels and restaurants are examples of such buildings. In addition, buildings with high specific cooling loads might be poor candidates for radiant cool-

TABLE 4.3. Office buildings in the largest metropolitan areas and their distribution with respect of the climate classification.

Climate	Occupied commercial area [$10^6 m^2$ (Msqft)]	Percentage of total	
group 1	11.1 (119.7)	5.05	
group 2	5.1 (54.4)	2.42	Dry climates
group 3	7.1 (76.7)	3.19	10.66%
group 4	17.2 (185.2)	8.31	
group 5	49.5 (532.9)	22.52	Moist climates
group 6	24.5 (263.6)	10.73	41.56%
group 7	49.1 (528.9)	24.69	
group 8	41.8 (449.4)	15.01	Humid climates
group 9	19.3 (208.0)	8.08	47.78%
Total	224.7 (2418.8)	100.00	

Source: Statistical Abstract of the United States 1995, Table 1229, “Commercial Office Space - Inventory and Vacancy Rates for the Largest Metropolitan Areas: 1994”

ing because the cooling power of radiant cooling systems is limited to 140 W/m^2.

Buildings that have poorly insulated envelopes fall into this category. Consequently, compatibility between the building equipped with the radiant cooling system and a certain climate group does not imply that the market for radiant cooling in the US covers the *entire* commercial building stock covered by that group.

Figure 4.7 presents a classification of the existing US commercial building stock by the main type of activity taking place in each building. The lighter area on Figure 4.7 represents buildings that are generally associated with large indoor moisture production (lodging, food sales, etc.), or buildings that might not need mechanical cooling (parking lots, some warehouses). The data in Figure 4.7 imply that, if buildings equipped with radiant cooling systems could function without the risk of condensation and were adequate to handle sensible loads in all US climate groups, the US market for radiant cooling would cover approximately 65% of the existing US commercial building stock.

4.4.4 The location-specific simulation periods

An estimate of the energy consumption and peak power demand of the radiant cooling

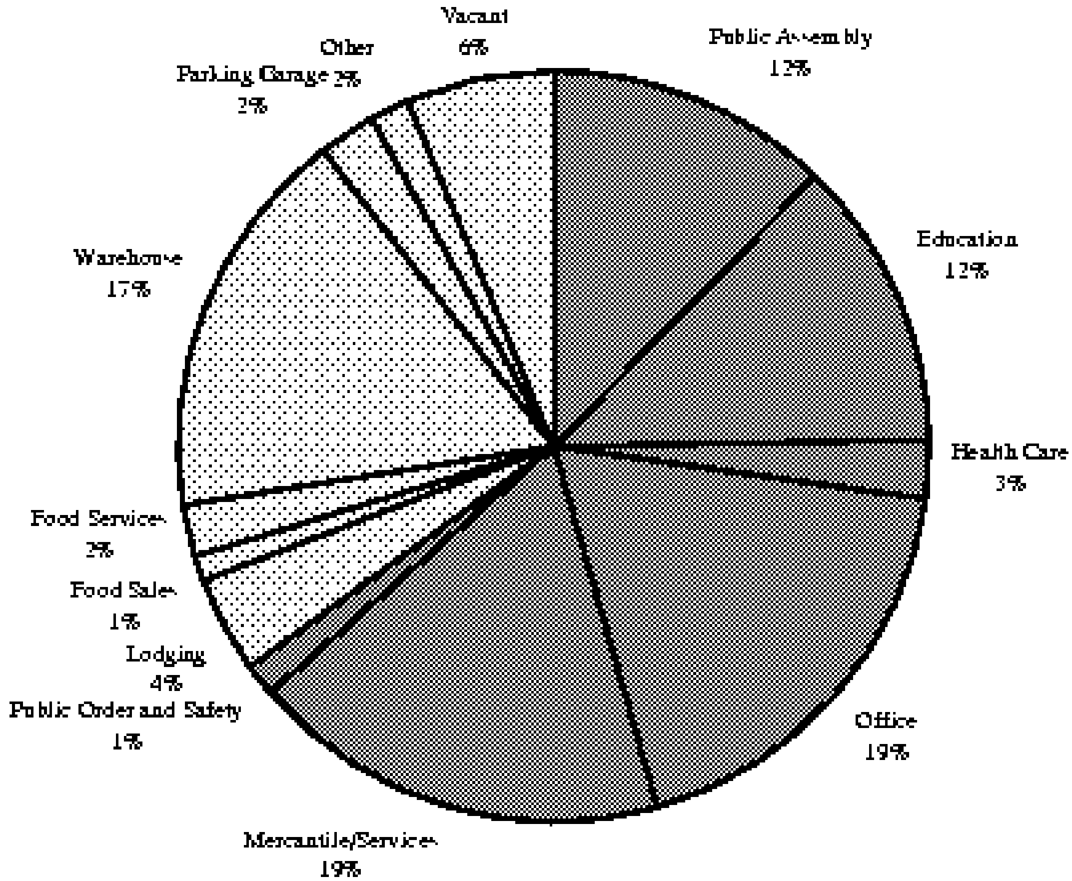

Figure 4.7. US commercial buildings - classification by principal activity.

Source: Statistical Abstract of the United States 1995, Table 1241, "Commercial Buildings - Selected Characteristics, by Square Footage of Floor Space: 1992"

system and the all-air system over the entire cooling season would provide the ideal data in the comparison of the performance of the two systems. However, RADCOOL simulations are limited to one week of weather data. If this modeling period is chosen at random, the extrapolation of the energy consumption and peak power demand from the selected week to the whole year has very little meaning. A selection process is therefore necessary to determine the location-specific week-long modeling period that best represents the climate characteristics of the entire cooling season.

Because the parametric study compares the energy consumption *and* peak power demand of a radiant cooling system with those of an all-air system that provides similar indoor conditions during occupancy hours, the selection process was conducted to choose *two* one-week periods at each location. The location-specific "typical week" reflects the average energy consumption of the all-air system over the cooling season. The location-specific “week of system peak” is a week centered around the day when the all-air system power demand is at its highest for the cooling season.

The typical week

The typical week is the location-specific week that reflects the average energy consumption of the air-conditioning system over the cooling season. The estimate for the system energy consumption during this week can therefore be considered generally representative of the system energy consumption over the cooling season.

Previous work. The challenge of establishing what is a “typical period of time” associated with estimating the energy consumption of a building first arose in the late 1970s. Several building energy simulation models had been generated by this time, but the computational capacity of computers limited the length of the simulation and/or the size of the building to be simulated. Progress in the computational power and capacity of computers has generally eliminated this issue in the last 10 years, except of course, for computational fluid dynamics (CFD) and programs such as RADCOOL. Continued efforts in the area of “typical weather” focus on establishing the characteristic weather at a given site by examining a large number of yearly data, describing weather trends, and creating “typical weather files” for building simulation programs. The weather files employed in the present study are the results of such efforts.

Recognizing the importance of the weather patterns on the energy consumption of a building, most of the early work on the topic of “typical weather” focused on performing some sort of “compression” of the available weather data. To this end, programs were designed that processed a full year of weather data and created a short version of each month. The simulation of a building using the resulting “typical weather” provided some information about the energy consumption of the building during the whole year.

A selection criterion is obviously needed to decide which days to select out of a year of weather data to generate the “compressed” months. The examination of two papers on the subject shows that different authors had different perspectives concerning the selection criterion.

Arens and Nall [8] focused on producing an algorithm that would be biased as little as possible towards any particular type of building or climate. Their technique estimated the impact of a number of weather parameters on the energy consumption of a building. After performing a large number of simulations, the authors were able to attach numerical weights to four weather parameters: dry-bulb temperature, humidity ratio, wind speed, and cloud cover. This allowed them to rank all the 4-day successions in a month, and then designate the 4-day period that best represents the month from the point of view of the building energy consumption. By comparing the energy consumption calculated using the compressed weather data with that calculated using the whole weather file, they showed that the error introduced in the prediction of energy consumption of a building by using the compressed data was approximately 3.5%.

Degelman [9] focused on matching his “compressed weather” data with a given set of buildings, both commercial and residential. By performing a large number of building simulations, he established the five weather parameters that most influence the energy consumption of a building: dry-bulb temperature, dew-point temperature, horizontal solar radiation, wind speed, and atmospheric pressure. He then identified the succession of 7 days in each month that introduces the least amount of error in predicting the number of degree days of heating and cooling at a given location. Finally, he tested his algorithm by performing a large number of simulations for different buildings and climates. His conclusion is that, for a given balance point temperature, the results obtained using the compressed weather file do not introduce more than 3% error in the estimate of energy use, regardless of the building type and climate used for simulations.

Both these papers show encouraging results of the use of compressed weather files. To obtain the compressed weather interval best suited for building energy consumption calculations, both procedures perform multiple simulations. In addition, both procedures rely heavily on the building energy use to determine the best selection criterion.

Procedure for determining the typical week of the cooling season. Due to the nature of RADCOOL, performing multiple simulations to establish the typical week at each location is out of the question. However, there are no such restrictions for performing multiple DOE-2 simulations for the building equipped with the all-air system.

As the energy consumption pattern of the radiant cooling system is probably different than the energy consumption pattern of the all-air system, the use of the energy consumption of the all-air system to designate the typical week may introduce errors in the results. However, the parametric study evaluates the energy consumption of the radiant cooling system and compares it with the energy consumption of the all-air system. Because the all-air system constitutes the basis of this comparison, it is not unreasonable to choose the typical week based on the energy consumption of the all-air system.

Since the typical week is location-specific, the following selection procedure was repeated for each of the 11 locations selected for the parametric study:

1. The base-case space equipped with the all-air system was simulated in DOE-2. The energy consumption of the all-air system was calculated for a pre-established cooling season (May 1 - October 31). The average seasonal energy consumption of the system as calculated was derived.

2. The average system energy consumption was determined for all the sliding weeks occurring in the cooling season. Sliding weeks are 7-day successions that start on each successive date; examples of sliding weeks are: May 1-7, May 2-8,..., October 25-31.

3. The difference between the weekly energy average and the seasonal energy average

was calculated for each sliding week.

4. The weeks were ranked according to the difference in the week-specific and seasonal energy averages.

5. The week with the lowest difference between the average weekly energy consumption and the average seasonal energy consumption was selected as the typical week. The estimate of the system energy consumption during this week provides the best approximation for the system energy consumption over the cooling season.

The typical weeks occur at the end of May through the beginning of June at 7 of the 11 selected locations, and at the end of August through the beginning of September at 4 of the 11 selected locations. This result is intuitively correct because, in contrast to the internal loads which remain approximately constant over the cooling season, the weather-induced cooling loads vary a fair amount. The mean behavior can be captured only by the weeks belonging to the “transition” (Spring or Fall) months.

The week of system peak

The week of system peak at each location is the week during which the power demand of the all-air system is the highest of the entire cooling season. The rationale for selecting the week of system peak based on the power demand of the all-air system is similar to that used to select the typical week. The time of the all-air system peak power demand can be easily established by performing a DOE-2 simulation for the entire cooling season. The time of the peak power demand of the radiant cooling system is difficult to determine because it is not practical to perform a RADCOOL simulation for the entire cooling season.

Performing the comparison between the peak power demand of the radiant cooling system and that of the all-air system during the week of system peak of the all-air system may introduce errors in the results of the study because the radiant cooling system may not reach its peak demand during the same week. In such a case the results of the comparison would indicate that the radiant cooling system has a larger potential to reduce the peak demand than it actually has. However, since the interior loads of the base-case space do not change during the simulated year, the time of the peak power demand should be driven by weather-induced loads (the conduction and solar heat gain through the facade). If this were true, the peak power demand of the radiant cooling system during the week of system peak of the all-air system may in fact coincide with the peak power demand of the radiant cooling system over the entire cooling season.

To determine the week of system peak the following procedure was repeated for each of the 11 locations selected for the parametric study:

1. The base-case space equipped with the all-air system was simulated in DOE-2 and the hourly power demand of the all-air system was calculated for the same pre-established cooling season (May 1 - October 31).

2. The time of the peak power demand of the all-air system was established at each location.

3. The week of system peak at each location was selected as the week centered on the day containing the peak power demand.

The base-case space equipped with the radiant cooling system was modeled in RADCOOL with the weather conditions imposed by the week of system peak. The hourly power demand was calculated and the time of the peak power demand was determined. In general, the peak power demand of the radiant cooling system occurs later than the peak power demand of the all-air system. The maximum time difference between the peaks is three hours.

The week of system peak is less location-specific than the typical week. The week of system peak occurs at the end of July through the beginning of August at all the selected locations. At all locations, the weather during the week of system peak is hot, and the humidity is at its highest. This indicates that weather-induced loads have significant influence on the time of the system peak demand.

Plausibility check

To verify that the procedure to select the typical week provides reasonable results, two tests were conducted. First, the difference between the average energy consumption during the week of system peak and the average energy consumption during the cooling season was calculated. At all 11 locations the differences between the two averages were large. Thus, the selection criterion for the typical week designates the week of system peak as “far from season average”.

Second, the energy consumption of the all-air system during the designated typical week was compared to the energy consumption of the system during the cooling season. At all 11 locations the energy consumption during the “typical” week represents 3.8% of the energy consumption over the established cooling season. The number of hours in a week (168) divided by the number of hours during the cooling season (4416) is also equal to 3.8%. The extrapolation of the energy consumption during the typical week to the energy consumption of the cooling season should therefore introduce little error, at least for the all-air system. In contrast, the week of system peak accounts for an average of 6.7% (the range over all locations is 4.5-9.6%) of the energy consumption over the cooling season. Extrapolating the energy consumption of the week of system peak to obtain the energy consumption of the cooling season would therefore lead to an over-estimate of the latter.

Discussion

Building simulations can determine the relationship between the energy consumption during the typical week and the energy consumption during the cooling season only for the all-air system. Due to the selection procedure, the relationship obtained is independent of the building location: the same factor of 3.8% links the air-conditioning energy consumption during the "typical" week to the air-conditioning energy consumption during the pre-established cooling season. However, the use of the 3.8% factor to predict the energy consumption of the radiant cooling system over the same cooling season implies that the energy consumption pattern of the radiant cooling system is similar to that of the all-air system. This assumption may be true, but has not been confirmed. This observation imposes the following restrictions on the interpretation of the results:

(1) It is reasonable to compare the radiant cooling system with the all-air system during the typical week of the all-air system. The result of this comparison provides an estimate for the difference in energy consumption of the two systems during this typical week. If this estimate is used to calculate the difference in the energy consumption of the two systems over the entire cooling season, the final result should be reported together with all the assumptions that were made to obtain it (Table 4.4).

TABLE 4.4. Summary of assumptions for the parametric study.

Assumptions	RADCOOL	DOE-2
Geographical locations	Figure 4.6 and Table 3.2	
Simulation periods	two week-long periods at each location (Section 4.4.4)	
Structure geometry, dimensions and orientation	base-case building: Figure 4.1 base-case space: MBC2 in Figure 4.1	
Window exposure	south-western	
Construction of vertical walls, roof and floor	Figure 4.3 and Table 3.1	
Window type	double-pane, U-value = 1.75 W/m^2-K	
Window shading	none	
Internal loads	22.5 W/m^2, 57% convective and 43% radiative	
Internal load schedule	8 a.m. to 5 p.m., Monday through Friday; no internal load on weekends	
Infiltration	0.2 ACH when space not ventilated	
Mechanical cooling	radiant panel system	VAV system

TABLE 4.4. (continued) Summary of assumptions for the parametric study.

Assumptions	RADCOOL	DOE-2
Cooling schedule	8 a.m. to 5 p.m., Monday through Friday no cooling on weekends	
Cooling system design strategy and setpoint	match indoor air temperature (24 °C ± 1 °C) and relative humidity (30 to 60%) during occupancy time	
Cooling air or water volume flow and inlet temperature	180 l/h 17.5 °C in Phoenix and Salt Lake City 20 °C at other 9 locations	variable volume variable temperature (not below 15 °C)
Ventilation air volume flow	Daytime: Monday through Friday: 36 m^3/h from 6 a.m. to 8 a.m. 72 m^3/h from 8 a.m. to 5 p.m., and 36 m^3/h from 5 p.m. to 6 p.m. weekends: 36 m^3/h from 6 a.m. to 6 p.m. Nighttime: 36 m^3/h from 6 p.m. to 6 a.m. or none, depending on ventilation strategy (Figure 4.5)	
Ventilation air inlet temperature	17.5 °C in Phoenix and Salt Lake City 20 °C at other 9 locations	variable temperature (not below 15 °C)

(2) The conclusions that can be drawn from the comparison of the two systems over the week of system peak and the typical week provide an initial indication of the potential of radiant cooling systems to reduce the energy consumption and peak power demand due to air-conditioning while providing similar indoor conditions as an all-air system. The generalization of these results requires further research.

4.5 Comparing the Results of the RADCOOL and DOE-2 Simulations

The parametric study compares the energy consumption and peak power demand of a radiant cooling system and an all-air system providing similar indoor air temperature and humidity to a commercial building. The study relies on RADCOOL simulations to obtain information regarding the performance of the radiant cooling system, and on DOE-2 simulations to describe the performance of the all-air system. In general, the use of two distinct programs to simulate two different systems may introduce uncertainties in the results. The parallel use of RADCOOL and DOE-2 in this study could not be avoided because at its present development stage DOE-2 is not able to simulate the performance of radiant cooling systems, and RADCOOL is not able to simulate the operation of a VAV system. However, the comparison of the results of RADCOOL and DOE-2 should not introduce significant uncertainties in the results because:

(1) both programs simulate the same base-case space with the same orientation and the same boundary conditions; Chapter 2 has described the intermodel comparison between RADCOOL and DOE-2 for a passive structure, and has shown that the two programs provide essentially the same results for the indoor conditions of this structure;

(2) the all-air system modeled in DOE-2 is designed to match the indoor air temperature and humidity obtained by the radiant cooling system simulation during occupancy time;[1]

(3) the same calculation strategy is used in the evaluation of the energy consumption and peak power demand of the two systems (see below).

1. To match the indoor conditions provided by the radiant cooling system, the design of the all-air system has to be finely-tuned (adjustments of the cooling coil temperature, supply temperature, recirculation air flow, etc. are needed). Common sense suggests that the fine-tuning process may change the energy consumption pattern of the all-air system and the time at the peak power demand occurs for this system. However, preliminary DOE-2 simulations show that the typical week and the week of system peak that would be selected after the fine-tuning has been achieved are the same as the typical week and the week of system peak that were selected before the fine-tuning has been achieved. The fine-tuning process does not appear to influence at all the results of the study.

4.5.1 Using the results of RADCOOL and DOE-2 to compare the energy consumption and peak power demand of the radiant cooling system and all-air system

The study uses the system parameters from the RADCOOL and DOE-2 simulations (air volume flow, supply air temperature, supply air humidity ratio, fan power, water volume flow, supply water temperature, and pump power), as well as weather parameters (air temperature, humidity ratio, solar radiation) to calculate the energy consumption and peak power demand of the radiant cooling system and all-air system, respectively. The assumptions of the study - a single-zone space conditioned by an air-conditioning system terminal - confine the energy and peak power accounting to space boundaries.[1] Thus the energy and peak power calculations carried by the study correspond to the readings of hypothetical space meters monitoring the sensible, latent, and distribution loads on the air-conditioning terminal due to its removing of sensible and latent heat from the base-case space.

Energy consumption and peak power calculation. The sensible load imposed on the air-conditioning terminal includes the power necessary to remove excess space heat, and to cool the outside air fraction necessary for ventilation. This translates into cooling the heat transfer medium used by each system (air for the all-air system, and air and water for the radiant cooling system) by a cooling coil. The thermal calculation consists of evaluating the power necessary to the cooling coil to cool a given volume flow of conditioning agent by the number of degrees equal to the difference between return temperature (specific to each calculation step) and supply temperature (dictated by the design supply setpoint). The volume flow of the conditioning agent is known at each time step.[2]

The latent load consists of the power necessary to remove excess latent heat from the space. The removal of excess latent heat is accomplished by controlling the moisture content of the air supplied to the space. The all-air system calculation evaluates the power necessary to the cooling coil to lower the moisture content of a given volume flow of supply air between mixing conditions (of outside and recirculation air) and design supply conditions. The radiant cooling system calculation evaluates the power necessary to lower the moisture content of the outside air volume flow between outside conditions and design supply conditions.

The distribution load of the all-air system consists of the fan power necessary to supply the cool air to the space. The fan power is calculated by DOE-2 for each hour when the system is active and is a function of the hourly air volume flow. The distribution load of the radiant cooling system consists of the pump power necessary to supply the cool

1. The “terminal” of the all-air system consists of the air supply register. The “terminal” of the radiant cooling system consists of the radiant surface and the ventilation air supply register.

2. The air volume flow supplied by the all-air system during work hours is variable (VAV system) and adjusted to the sensible loads of the space, and is constant or zero during off-occupancy hours. The air volume flow and water volume flow supplied by the radiant cooling system are constant or zero by design.

water to the radiant cooling panels, and the fan power necessary to supply the ventilation air to the space. The pump and fan power of the radiant cooling system are constant when operated.

To provide a basis for the comparison of the energy consumption and peak power demand of the all-air system and radiant cooling system, all three components of the load on the air-conditioning terminal (sensible, latent, and distribution) should be expressed in the same units. As the results of the calculation correspond to the readings of energy and power meters, the units of choice are those of electrical energy (kWh_e) and electrical power (W_e).

The distribution load is already expressed in terms of electrical power demand. However, the sensible and latent loads are expressed in terms of thermal power demand. Converting these units in terms of electrical power demand requires an assumption about the coefficient of performance (COP) of the cooling coil-chiller combination serving each system. For simplicity, the study used a constant COP for the both the cooling coil-chiller combination serving the radiant cooling system and for that serving the all-air system. In reality, the COP varies as a function of the load. The numerical value of the COP of commercially-available chillers varies between 2.5 (for rooftop units) and 5 to 6 (for centrifugal chillers) at design point [10]. The parametric study uses a COP of 3 in its thermal-to-electric conversion calculations.

Comparing the energy consumption and peak power demand of the two systems. The comparison of the peak power demand of the all-air system and the radiant cooling system consists of (1) calculating the electrical sensible, latent, and distribution loads for each hour of the week of system peak, (2) determining the hour when the peak electrical load occurs for each system separately, and (3) evaluating the difference between the peak load of the all-air system and that of the radiant cooling system.

The comparison of the energy consumption of the all-air system and radiant cooling system consists of (1) calculating the electrical sensible, latent and distribution loads for each hour of the typical week, (2) summing these values and multiplying by the time step to evaluate the electrical energy consumption during the typical week for each system, and (3) evaluating the difference between the energy consumption of the all-air system and that of the radiant cooling system.

The results of the energy and peak power calculation are presented in Appendix B and will be discussed in Chapter 5.

4.6 Capabilities and Limits of the Parametric Study

The goals of the parametric study described in this Chapter are (1) to establish whether buildings equipped with radiant cooling systems can function in US climates without the risk of condensation, and (2) to compare the energy consumption and peak power demand of a radiant cooling system and an all-air system that provide similar indoor conditions to a commercial building space during occupancy time. Due to the design of the parametric study, the comparison of the results obtained for the building equipped with the radiant cooling system and the building equipped with the all-air system will mainly reflect the difference between the performance of the two systems. It is worthwhile to note, however, that the results are influenced by the type of building in which the two systems operate, as well as by the building location, internal loads, etc. The study captures the climate-variability of its results by repeating the simulations and performing the comparison of the results at a number of “typical” locations. Assumptions and limitations notwithstanding, this parametric study is the first in-depth investigation into the climate-related aspects of the performance of buildings equipped with radiant cooling systems. Further research is necessary to generalize the results to any building type, as well as into other “dimensions”. The capabilities and limits of the study are summarized below.

Capabilities: the study

(1) proposes a methodology for the comparison of the simulated energy consumption and peak power demand of two different building conditioning systems;

(2) conducts parallel simulations of a radiant cooling system and an all-air system for several US climates; investigates the potential of the radiant cooling system to use less energy and require less peak power to condition a base-case space;

(3) investigates the capability of radiant cooling systems to operate in US climates with a small risk of condensation; establishes climate-dependent trends in the energy consumption and the peak power demand of a radiant cooling system;

(4) reflects the indoor conditions of a selected space in a new office building structure;

(5) adds to the present state of knowledge about how buildings equipped with radiant cooling systems might function;

(6) can be extended to include other building types, locations, simulation periods, etc., when the calculation capacity of computer improves;

(7) can be adapted to specific projects and can be used in building design decisions as soon as RADCOOL and DOE-2 are integrated.

Limits: the study

(1) uses RADCOOL to simulate the performance of the radiant cooling system; this limits the study to:

- one building having pre-established structure and layout;

- one space having a “rationally” pre-established orientation, occupancy rate, interior loads, boundary conditions, and cooling system design;

- two study periods limited to one week of weather data each;

- a small number of locations;

(2) uses DOE-2 to simulate the performance of the all-air system; this restricts the use of comfort parameters as matching parameters for the indoor conditions simulated by the two programs to the indoor air temperature and humidity;

(3) does not cover all possible US building locations;

(4) does not cover all possible system designs and chiller performance coefficients (COP);

(5) does not provide information regarding the response of the radiant cooling system to sudden internal load changes (such as a case in which several people walk into a conference room for a meeting);

(6) does not provide information regarding the performance of the radiant cooling system in buildings with high internal loads, in buildings with poorly insulated structures, or in buildings with significant indoor or outdoor sources of moisture;

(7) introduces uncertainty into the extrapolation of its results to the whole base-case building, and/or to the entire cooling season at each location; this uncertainty has many components (e.g. relationship between space air-conditioning energy consumption and building air-conditioning energy consumption, relationship between the energy consumption of radiant cooling system during the designated typical week and during the entire cooling season, time of peak power demand of the radiant cooling system), and each component is difficult to estimate.

4.7 References

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